GAP, an accelerometer package for Laplace and Tandem missions

Bruno Christophe, B. Foulon, A. Levy, J. Anderson, T. Sumner, O. Bertolami, P. Gil, J. Páramos, S. Progrebenko, L. Gurtvis, et al.

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GRAVITY ADVANCED PACKAGE, AN ACCELEROMETER PACKAGE FOR LAPLACE OR TANDEM MISSIONS

Christophe, B.[1], Foulon, B.[1], Levy, A.[1], Anderson, J.D.[2], Sumner, T.J.[3], Bertolami, O.[4], Gil, P.[4], Paramos, J.[4], Progrebenko, S.V.[5], Gurtvis, L.[5], Reynaud, S.[6], Courty, J-M.[6], Asmar, S.W.[7], Métris, G.[8], Bério, P.[8], Bingham, R.[9], Kent, B.[9], Olsen, O.[10], Andersen, P.H.[10], Dittus, H.[11], Lämmerzahl, K.[11], Theil, S.[11], Rievers, B.[11] and Bremer, S.[11]

Abstract. The Einsteinian theory of gravitation, General Relativity (GR), is well verified at scales ranging up to the size of planetary orbits but it is challenged by larger-scale observations. In the Solar System, several anomalies have also been detected in the trajectories of some spacecraft: a small anomalous Doppler acceleration has been detected on Pioneer 10 and 11, and several spacecrafts have an unpredicted increment of velocity after their Earth flyby. Therefore, it is extremely interesting to test the gravity laws at interplanetary scales in the solar system.

In the frame of Cosmic Vision selection, the Fundamental Physic Advisory Group of ESA suggested to use an accelerometer, as presented in Odyssey mission proposal, on the future interplanetary mission, Laplace or Tandem mission, pre-selected by ESA, in order to achieve this scientific objective.

For such objective, an accelerometer without bias is mandatory in order to discriminate between conventional forces applied on the spacecraft and gravity forces, in the low-frequency domain. The Gravity Advanced Package takes advantage of mature technology developed at ONERA for ultra-sensitive accelerometry and a bias rejection system is added in order to obtain the performance in the expected bandwidth.

1 Introduction

The Einsteinian theory of gravitation, General Relativity (GR), is well verified at scales ranging up to the size of planetary orbits but it is challenged by larger-scale observations. Gravitational anomalies are indeed observed in the rotation curves of galaxies and also in the relation between red-shifts and luminosities of supernovae. These anomalies (deviations between observed and expected behaviors) are interpreted as revealing the presence of dark components in the content of the Universe, but the observed anomalies can as well be consequences of modifications of GR at galactic or cosmic scales. Given the immense challenge posed by these large scale behaviors, it is important to explore any possible option. It is in particular extremely interesting to test the gravity laws at the largest possible distances, that is practically speaking at interplanetary scales in the solar system.

Odyssey (Christophe 2008) was submitted by large international teams to ESA in response to the Cosmic Vision 2007 call, with the aim of testing gravity laws in the deep solar system, beyond the orbit of Saturn.

[1] ONERA/DMPH, 29, av. Division Leclerc, F-92322 Chatillon
[2] Global Aerospace, USA
[3] Imperial College, London, UK
[4] Instituto Superior Técnico, Lisboa, Portugal
[5] Joint Institute for VLBI in Europe, The Netherlands
[6] Laboratoire Kastler Brossel, ENS, UPMC, CNRS, Paris, France
[7] NASA, JPL, Pasadena CA, USA
[8] Geoscience Azur, Université Nice-Sophia Antipolis, Observatoire de la Côte dAzur, Grasse, France
[9] Rutherford Appleton Laboratory, Didcot, UK
[10] University of Oslo, FFI, Norway
[11] ZARM, University of Bremen, Germany

Though the proposal was not selected as dedicated mission, its scientific objectives were supported by the Fundamental Physics Advisory Group and a recommendation issued by ESA for embarking an accelerometer similar to that designed for Odyssey on-board one of the planetary missions selected LAPLACE or TANDEM.

The two missions have their main objectives devoted respectively to the systems of Jupiter and Saturn. They will explore heliocentric distances up to 5 AU and 9 AU respectively. Their trajectories will take benefit of several gravity assists at Earth and other planets. Embarking an accelerometer on-board one of these planetary missions would allow one to meet some of the objectives of the Odyssey project without waiting for a dedicated mission: the solar system gravity test and the flyby investigation.

2 Scientific Objectives

2.1 The solar system gravity test

Such a test has been performed by Pioneer 10/11 probes during the extended missions decided by NASA after their primary planetary objectives had been met. This largest scaled test of gravity ever performed has failed to reproduce the expected variation of the gravity force with distance due to the presence of a small anomalous Doppler acceleration (time derivative of the Doppler velocity). This deviation from the predictions of GR can be interpreted as an unexpected Sunward acceleration with a nearly constant magnitude of 0.87 ± 0.13 nm/s^2 for probes beyond the orbit of Saturn. This signal has become known as the "Pioneer Anomaly" (Anderson et al. 2002) and has been confirmed by independent analysis of the Doppler data (Levy et al. 2008). Although the most obvious explanation would be a systematic effect, the extensive analysis performed by J. Anderson et al at JPL did not support any of the numerous mechanisms which were considered (Anderson et al. 2002). Investigations have been initiated for confronting the Pioneer data with other gravity tests in the solar system as well as analyzing the potential significance of the anomaly for fundamental physics, solar system physics or astrophysics (Jaekel & Reynaud 2006; Brownstein & Moffat 2006; Bertolami & Paramos 2004).

Modern planetary probes are navigated with radio-metric tracking (Doppler and range measurements) as the main tool for producing precise orbit determination and prediction. The accelerometer of the Gravity Advanced Package provides the navigators with a direct measurement of non-gravitational forces, thereby eliminating the uncertainties in the models currently used to deal with these forces, and then leading to a better accuracy and reliability in orbit reconstruction. It represents a major improvement with respect to the navigation in the solar system and solve interpretation ambiguity on the nature of the results in an immediate manner. It also allows one to perform measurements at earlier phases of the mission, when the solar effects are still much larger than the looked for accelerations.

In the GAP experience, the resolution havs been fixed at a value of 0.05 nm/s^2 that is 5% of the recorded Pioneer anomaly.

2.2 The flyby investigation

In most recent missions using Earth gravity assistance (EGA), NASA (Antreasian & Guinn 1998) and ESA (Morley & Budnik 2006) navigation teams have noticed that the spacecraft possesses after the fly-by a velocity larger than calculated from the precisely measured initial conditions and the known properties of the Earth gravity field. The anomalous additional velocities ΔV corresponding to this "flyby anomaly" reach values up to 13 mm/s for the first EGA of the NEAR probe. The various systematic effects which could spoil the effect (the gravity field of the Earth, atmospheric drag, charging and Earth tides, etc) have to be studied in a careful manner, but are thought (Lammerzahl et al. 2008) to result in uncertainties well below the measured ΔV. Very recently, an empirical formula has been proposed which relates the anomaly to a planet-dependent constant and to the incoming and outgoing geocentric latitudes of the asymptotic spacecraft motion (Anderson et al. 2008). This formula can now be used to predict the magnitude of the anomaly. Another important objective is to compare gravity assists at Earth and other planets in order to correlate their constants with the physical properties of the planets.

With the accelerometer on board, the non gravitational acceleration will be measured during the whole fly-by, including the typical DSN black-out period. It will enable an unambiguous characterization of the nature of the fly-by anomalies, and either confirm the presence of the anomaly or solve the discrepancy, then leading to a significant improvement of our capabilities in trajectory prediction and navigation. The velocity increment ΔV will be measured by the radio-tracking system before and after the fly-by with a precision of 10 μm/s, which is less than 1% of the typical anomalous ΔV registered in the presently available analysis.

3 μSTAR accelerometer description

The Gravity Advanced Package is light-weight, small, and has low power consumption (3kg, 3l, 3W, including the bias compensation mechanism and the interfaces). Its core is an accelerometer benefiting from the Onera design heritage that was successfully used in many recent space experiments CHAMP, GRACE and GOCE (Touboul et al. 2004). The main challenges are the development of the bias calibration system and the integration of the package in the spacecraft.

3.1 Accelerometer Sensor

Three axis electrostatic accelerometers developed at ONERA are based on the electrostatic levitation of the instrument inertial mass with almost no mechanical contact with the instrument frame. Measurements of the electrostatic forces and torques, which result from the six servo-loops necessary to maintain the mass motionless with respect to the sensor cage, provide the six outputs of the accelerometer. The relative motion of the proof-mass (6 degrees of freedom) is in fact finely measured by capacitive sensors with respect to the sensor silica core selected for its very high geometric stability. Whatever is along the orbit the charged particles radiation, the electrical potential of the mass is maintained at a constant level to linearize the actuators. The control of the proof-mass is performed by low consumption analogue functions. The outputs of the accelerometer, which are the applied voltages on the electrodes to control the proof-mass, are sent to an Interface Control Unit.

The bias rejection system is similar to rotating stage existing on the shelf, but optimized in order to reduce the mass and the consumption. This system consists of a flip mechanism to create a $\pm 180°$ rotation of the accelerometer sensitive axes with respect to the satellite ones at regularly spaced times. As a consequence, the resulting modulation of the measured accelerations projected on the instrument sensitive axes allows to distinguish the applied acceleration on the satellite from the accelerometer bias, the latter staying at DC while the first is transposed at the modulation frequency.

3.2 Instrument Performance

The total error budget of the instrument package includes the following main limitation sources:

Accelerometer noise: Taking advantage of the previous instrument development and models, the instrument characteristics can be evaluated on the basis of the selected configuration for the sensor core and the electronics functions. Over one day, the integrated noise, along one sensitive axis considering a thermal stability of $1°\mathrm{C/Hz}^{1/2}$ at 0.01 mHz is 0.01 nm/s^2 rms. In this configuration, the accelerometer full range is 20 μm/s^2.

Misalignment of accelerometer axes: The misalignments of the accelerometer axes with respect to the ones of the spacecraft, given by the star tracker lead to errors proportional to the maximal non-gravitational acceleration applied on the spacecraft. Considering a one ton spacecraft, with a 30 m^2 surface of solar panel, the impact of misalignment is less than 0.01 nm/s^2 at 2 AU, with a requirement of misalignment less than 0.2 mrad.

Error of bias rejection: The error of the bias evaluation and rejection comes from the non perfect rotation of the instrument with respect to the considered one in the processing, the post-processing limitation, the evolution of the bias and non-gravitational acceleration during the processing period and the effect of the external acceleration signals at harmonics of the flip frequency. The total error due to the bias rejection system and the post-processing should be less than 0.02 nm/s^2.

Coupling with spacecraft angular motion: As the sensitive centre of the accelerometer (centre of gravity of the proof-mass) will not be perfectly co-localized with the centre of gravity of the spacecraft, a coupling term with the angular motion of the spacecraft will perturb the linear acceleration measurement. This term could be corrected according to the knowledge of the relative position of the accelerometer with respect to the centre of gravity of the spacecraft and to the estimate of the angular motion of the spacecraft from the star tracker quaternions. Requirement on the residue of this term evaluation has been considered to be 0.04 nm/s^2. Considering a decentring of the accelerometer of 0.5 m, known with 1 cm accuracy, a star tracker accuracy of 10 arcs, the attitude control of the spacecraft should be better than 0.15° from DC to 0.1 mHz.

Spacecraft self-gravity: All the masses around the accelerometer will attract the proof-mass and creates a parasitic acceleration, the satellite self-gravity: this acceleration cannot be rejected by the rejection system as its direction is linked to the spacecraft and not to the accelerometer. This contributor shall be less than 0.01 nm/s^2. If too large, it can be estimated according to the satellite design but nevertheless has to be limited either by a good symmetric architecture or by a good knowledge of the steady mass repartition of the components around the accelerometer in order to reduce the estimation residue.

A supplementary 0.01 nm/s^2 error is added for all other error sources, not detailed here above.

4 Conclusions

It has to be emphasized that the presence of the accelerometer on-board not only enables fundamental physics objectives to be met, but also constitutes an invaluable complement to the planetary mission in terms of navigation as well as knowledge of the gravity field and environment of the visited planets and moons. After a more detailed study with specialists of these scientific questions, this can be used to increase the scientific return for some solar system physics objectives. First, the accurate measurements of the surface forces during the cruise phase can be translated into an improved knowledge of solar system environment. The same conclusion holds for measurements in the vicinity of the planet or its moons. Then the improved reconstruction of the orbits around the planet, thanks to the presence of an accurate accelerometer on board, should result in a determination of the gravity field of the planet or its moons (like in Earth gravity mission CHAMP (Touboul et al. 1998), with potentially new information of major interest for the study of these bodies.

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